Constraints on unparticle physics from the $gt\bar{t}$ anomalous coupling

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Abstract

We study the impact of unparticle physics to the chromomagnetic dipole moment (CMDM) of the top quark. We compute the effect induced by unparticle operators of scalar and vector nature coupled to fermions on the CMDM. We find that this dipole moment is sensitive to the scale dimensions d_u of the unparticle and the new couplings of the respective effective operators. Using the bounds imposed on the CMDM by low-energy precision and Tevatron measurements we derive indirect limits on the unparticle parameter space. In particular, we find that the scalar-unparticle operator contribution fulfills both constraints for most of the unparticle parameter space, while the low-energy precision bound on the CMDM excludes a vector-unparticle contribution for low values of respective scale dimension d_u.

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One of the main goals of the CERN Large Hadron Collider (LHC) is to study the properties of the top quark with significant precision since more than 80 millions of top-quark pairs will be produced with an integrated luminosity of 100 fb^{-1} [1]. In particular, the interest in the study of its chromomagnetic dipole moment (CMDM) $\Delta\kappa$ has increased recently since it was realized that the presence of no-standard model couplings could lead to modifications in the total and differential cross sections of top-quark pairs at hadron colliders [2]-[8]. The effect of $\Delta\kappa \neq 0$ has been examined in the Standard Model, two Higgs doublets models (THDM), top-color assisted Technicolor (TC2) models, 331 models, extended models with a single extra dimension [9], and in the littlest Higgs model with T-parity (LHT) [10]. In all these cases, it has been found that their predictions for $\Delta\kappa$ are consistent with the constraints imposed on $\Delta\kappa$ by low-energy precision measurements obtained from the $b \to s\gamma$ process $\Delta\kappa = -0.01 \pm 0.048$ at 95% C.L.[11], and by the cross section measurements of the Tevatron for $t\bar{t}$ pairs, $|\Delta\kappa| \leq 0.20$ [12]. In the present letter, we compute the contribution induced on $\Delta\kappa$ by scalar and vector unparticle operators [13]. Assuming the known bounds on $\Delta\kappa$ obtained from the $b \to s\gamma$ process[11, 12], we derive limits on the scalar- and vector-like unparticle dimensions (d_u) and the new scale Λ that characterizes these interactions. We find that these limits are similar to those obtained from cosmological and astrophysical processes [14], CP-violating effects in B decays [15], Z boson decays [16] and the Tevatron measurements for $t\bar{t}$ production [17].

Scale invariance has been a powerful tool in several branches of physics. Scale invariant field theories have been investigated also extensively. In particular, Georgi [13] has proposed that a scale invariant sector, with no trivial IR fixed point and which couple to the SM fields, may appear much above the TeV energy scale. Below this energy scale, this sector induces unparticle operators $\mathcal{O}_{\mathcal{U}}$ with non-integral scale dimensions d_u that in turn have a mass spectrum which looks like a d_u number of massless particles. The couplings of these unparticles to the SM fields are described by the effective Lagrangian [18, 19]

$$\begin{aligned}\mathcal{L}_{eff} \sim & \frac{\zeta_S}{\Lambda^{d_u-1}}\bar{t}t\mathcal{O}_U + \frac{i\zeta_A}{\Lambda^{d_u-1}}\bar{t}\gamma_5 t\mathcal{O}_U \\ + & \frac{C_V}{\Lambda^{d_u-1}}\bar{t}\gamma_\alpha t\mathcal{O}^\alpha_U + \frac{C_A}{\Lambda^{d_u-1}}\bar{t}\gamma_\alpha\gamma_5 t\mathcal{O}^\alpha_U, \end{aligned} \tag{1}$$

where Λ is the energy scale at which scale invariance emerges, the dimensionless coefficients $\zeta_{S,A}$ and $C_{V,A}$ are of order 1 and t is the top-quark spinor. Since the operators with lowest possible dimension have the most powerful effect in the low energy effective theory, in Eq.

(1) we have included only the scalar and vector operators $\mathcal{O}_U$ and $\mathcal{O}_U^\alpha$, respectively, of the unparticles that couple to the quark-top.

If the source of this new physics is at the TeV scale, it has been pointed out [3] that the leading effect on the top quark-gluon interaction may be parametrized by the chromo-magnetic dipole moment (CMDM) $\Delta\kappa$ of the top quark since this is the lowest dimension CP-conserving operator arising from an effective Lagrangian contributing to the gluon-top-quark coupling,

$$\mathcal{L}_5 = i(\Delta\kappa/2)(g_S/2m_t)\bar{t}\sigma_{\mu\nu}q^\nu T^\alpha t G^{\mu,\alpha} \tag{2}$$

where g_S and T^α are the $SU(3)_c$ coupling and generators, respectively, and the gluon is on-shell.

We consider that the scalar and vector unparticle mediation is responsible for the CMDM and we predict the appropriate range for the free parameters appearing in the effective Lagrangian which drive the unparticle-SM quark interactions. We will obtain that $\Delta\kappa$ is strongly sensitive to the scaling dimension d_u of the vector unparticle operator and the new unparticle-SM top quark couplings given in Eq. (1).

The scalar unparticle propagator is obtained with the help of scale invariance and using the two point function of the unparticle [14, 19],

$$\begin{aligned}\int d^4x\, e^{ipx} \, <0|T\Big(O_U(x)\, O_U(0)\Big)0> &= i\frac{A_{d_u}}{2\,\pi}\int_0^\infty ds\,\frac{s^{d_u-2}}{p^2-s+i\epsilon}\\ &= i\,\frac{A_{d_u}}{2\,sin\,(d_u\pi)}\,(-p^2-i\epsilon)^{d_u-2}\,,\end{aligned} \tag{3}$$

with

$$A_{d_u} = \frac{16\,\pi^{5/2}}{(2\,\pi)^{2\,d_u}}\,\frac{\Gamma(d_u+\frac{1}{2})}{\Gamma(d_u-1)\,\Gamma(2\,d_u)}\,. \tag{4}$$

The scale dimension d_u is restricted in the range $1 < d_u < 2$. Here, $d_u > 1$ is due to the non-integrable singularities in the decay rate [14] and $d_u < 2$ is due to the convergence of the integrals [19].

The contribution induced by the scalar unparticle operator to the CMDM (Fig. 1) is given by

$$\Delta\kappa^{\mathcal{O}_U} = \left(\frac{1}{\Lambda_u^{d_u-1}}\right)^2 \frac{A_{d_u}}{\sin(d_u\pi)}\frac{(2-d_u)}{4-d_u}\frac{m_t^2}{8\pi^2}$$

$$\times \int_0^1 dx \int_0^{1-x} dy \frac{(1-x-y)^{1-d_u}}{(m_t^2(x+y)^2)^{2-d_u}}$$
$$(x+y)\left((-2+x+y)\zeta_S^2-(x+y)\zeta_A^2\right) \tag{5}$$

while the vector unparticle operator contribution to the CMDM is

$$\begin{aligned}
\Delta\kappa^{\mathcal{O}_U^\alpha} &= \left(\frac{1}{\Lambda_u^{d_u-1}}\right)^2 \frac{A_{d_u}}{\sin(d_u\pi)}\frac{m_t^2}{8\pi^2}\int_0^1 dx \int_0^{1-x} dy \frac{(1-x-y)^{1-d_u}}{(m_t^2(x+y)^2)^{2-d_u}} \\
&\times \Big\{\Big([-2x(1-2y-x)-2y(1-y)]\,C_V^2 \\
&+ [8+2x(-5+2y+x)-2y(5-y)]\,C_A^2\Big) \\
&+ \frac{(1-x-y)}{(x+y)^2}\Big(\Big[x^2(x+1+y)+y^2(y+1+x)+xy\Big]\,C_V^2 \\
&+ \Big[x^2(x-1-5y)+y^2(1-y)+xy\Big]\,C_A^2\Big) \\
&+ \frac{4(1-x-y)}{2-d_u}\Big(\Big[3y^2+3x^2+2y+2x+4xy-2\Big]\,C_V^2 \\
&+ \Big[3y^2+3x^2-4x+3xy+2\Big]\,C_A^2\Big)\Big\}
\end{aligned} \tag{6}$$

The SM predicts, at the one loop level [9], $\Delta k^{SM} = -0.056$. In order to get the respective predictions of the scalar and vector unparticles to the CMDM, we have to add to the SM CMDM the values obtained with the expressions given in Eqs. (5) and (6). In Fig. 2 we depict the SM plus the respective scalar unparticle contribution to the CMDM for different choices of the coefficients $\zeta_{S,A}$. We have found that all three possible combinations for the unparticle coefficients $C_{S,A}$ induce negative values for the CMDM that are consistent with both bounds on $\Delta\kappa$ coming from the Tevatron and the $b \to sg$ decay measurements [11, 12]. On the other hand, we can appreciate in Fig. 3 that the latter bound already induces significant constraints on the purely axial-vector ($C_V = 0, C_A = 1$) and quiral ($C_V = 1, C_A = 1$) operator contributiuons to the top-quark CMDM, while the vector contribution ($C_V = 1, C_A = 0$) satisfies both bounds except for low values of the vector scale dimension d_u of order $1.0-1.2$. A similar sensitivity for small values of the scalar-unparticle dimension d_u has been also observed for the lepton-flavor conserving Z boson decays [16]. In Fig.4 we have depicted also the vector-unaprticle plus SM contributions to $\Delta\kappa$ for a higher value of the scale energy Λ. We can appreciate that the constraints on the vector-unparticle contributions are not very senstitive to this energy scale. However, for this energy scale all three combinations of the vector-unparticle operators satisfy both limits on $\Delta\kappa$, except for low values of the respective scale dimension d_u.

In conclusion, we have studied the effect of scalar and vector unparticle operators to the quark top CMDM at the one-loop level. We have found that this dipole moment is sensitive to the values of the respective unparticle dimensions d_u and the low energy scale Λ. We have used the bounds imposed on the top-quark CMDM by the low-energy precision constraints [11] and the Tevatron measurements [12] in order to get limits on the unparticle parameter d_u and Λ. We would like to mention that our limits on the vector unparticle dimension d_u are similar to those obtained from FCNC processes involving a quark-unparticle interaction in the context of CP-violation effects in B decays [18], lepton-flavor conserving decays of the Z boson [19] and the current Tevatron measurements for $t\bar{t}$ production[16].

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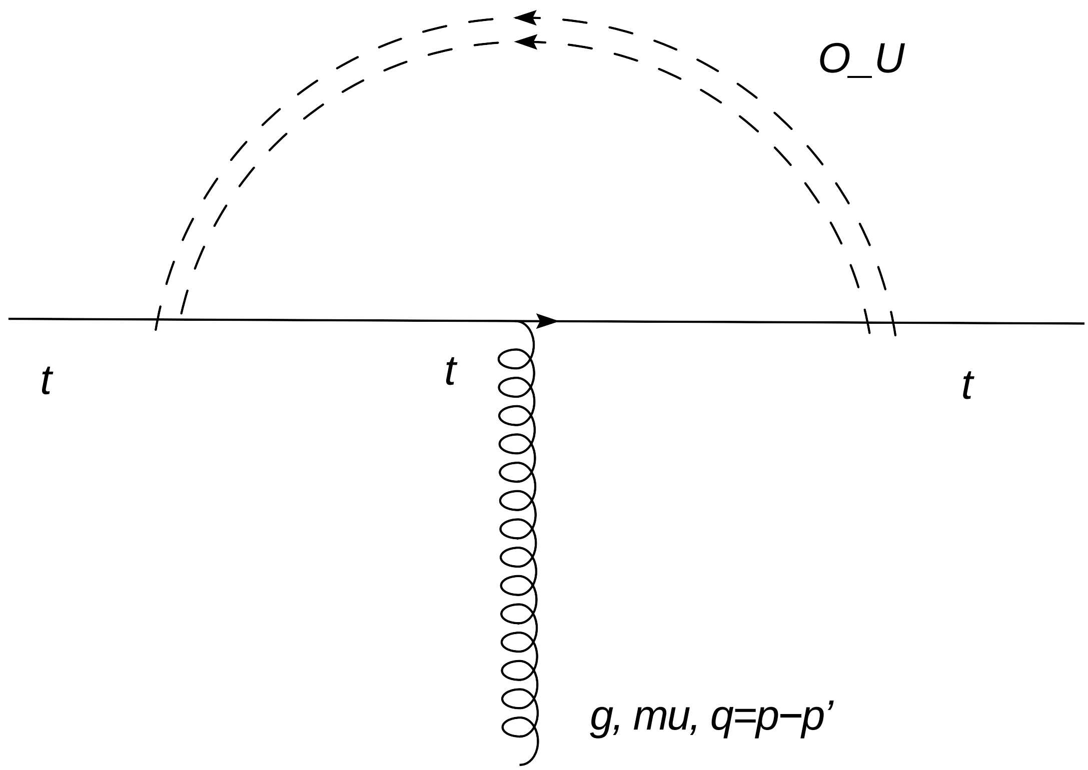

FIG. 1: Feynman diagrams for the contribution of the scalar and vector unparticles to the CMDM of the top quark.

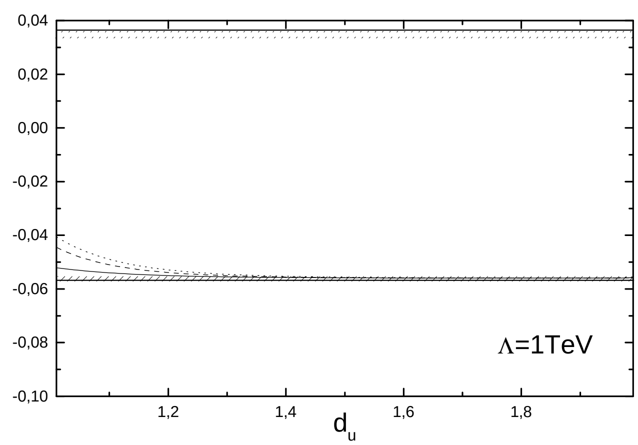

FIG. 2: The top-quark CMDM $\Delta\kappa$ as a function of the scalar unparticle dimension d_u, with $\Lambda = 1TeV$, for purely scalar (solid line, $\zeta_S = 1, \zeta_A = 0$), purely pseudoscalar (dashed, $\zeta_S = 0, \zeta_A = 1$) and the quiral combination (dotted, $\zeta_S = \zeta_A = 1$) of the particle operator. The solid stright lines give the limit induced on $\Delta\kappa$ from the $b \to s\gamma$ decay at 95% C.L..

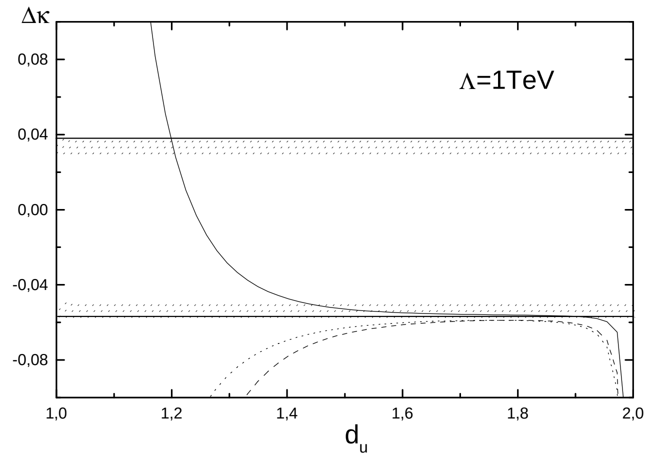

FIG. 3: The CMDM of the top quark as a function of d_u with $\Lambda = 1$ for purely vector (solid line, $C_V = 1, C_A = 0$), axial vector (dashed $C_V = 0, C_A = 1$) and the quiral combination (dotted, $C_V = C_A = 1$) of the vector-unparticle operator. The horizontal lines denote the limit obtained for $\Delta\kappa$ from the $b \to s\gamma$ decay at 95% C.L..

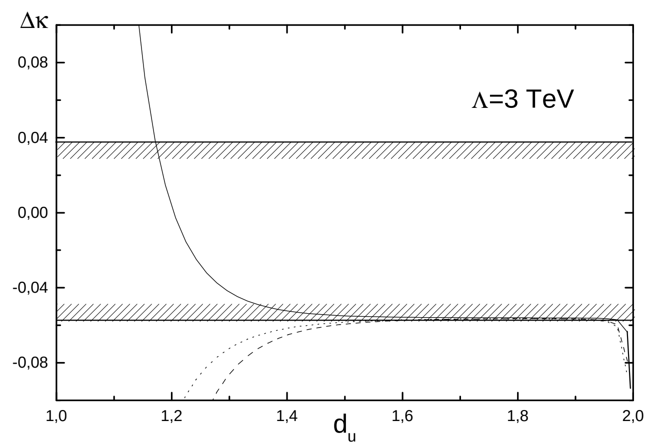

FIG. 4: Dependence of the vector-unparticle operator contributions to the CMDM of the top quark for the scale energy $\Lambda = 3$ TeV. We use the same conventions as in Fig.3.